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PYROTECHNIC FLARE SPECTROSCOPY
A RADIATIVE TRANSFER MODEL

by
Bernard E. Douda

NAVAL AMMUNITION DEPOT
APPLIED SCIENCES DEPARTMENT
CRANE, INDIANA 47522

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A two-line radiative transfer model for predicting the spectral radiant flux of pyrotechnic illuminating flares over a wide range of system variables such as formula, size, and ambient pressure, has been formulated and validated.

To solve the transfer equation for observed radiant intensity, the flame is represented by a model whose main characteristics are (a) the

flame is a homogeneous gaseous atmosphere with plane-parallel stratification, (b) the gas consists of inert molecules plus sodium atoms which can be excited to the $^2P_{\frac{1}{2}}$ or $^2P_{\frac{3}{2}}$ level, (c) there is local thermodynamic equilibrium governed by the local temperature, (d) the temperature gradient can be represented by a parabola whose vertex is at the center of the flame, (e) the dispersion profile and number density of sodium atoms have average values, inside the flame, that are independent of depth, and (f) the individual line dispersion profile is replaced with a two-line function to simultaneously describe the spectral distribution of both of the sodium D lines.

The parameters of the radiative transfer theory were supplied from calculated thermodynamic properties of the flare. Optical thickness as a function of position in the flame was determined using computed sodium atom densities and physical flame size obtained photographically. A flame temperature gradient was constructed numerically as a function of temperature in the flame using the computed temperature at the flame center and the boundary. The two-line dispersion profile was constructed as a function of line broadening. The shape and intensity of the broadened flare spectrum was computed without introducing further assumptions.

FOREWORD

This paper was prepared for presentation at the annual NAVAIR review of its sponsored research programs in the field of Energy Conversion (non-propulsive aspects) to be held on 26-27 March 1974, at the Denver Research Institute, University of Denver. The work is sponsored by the Research and Technology Group of the Naval Air Systems Command. Dr. Hyman Rosenwasser is the Program Manager in NAVAIR.

The progress report for fiscal year 1972 is contained in RDTN No. 223, "Pyrotechnic Flare Spectroscopy III", Naval Ammunition Depot, Crane, Indiana, 1 November 1972.

INTRODUCTION

Illuminating flares are typically made from a mixture of magnesium, sodium nitrate, and a binder. Light is emitted from these flares at a luminous efficiency of about 50,000 candle-seconds/gram. To satisfy the continuing need to generate light more efficiently, the specific objective of this research was directed toward determining the mechanisms by which light is emitted from illuminating flames, the new knowledge providing the basis for future improvements. In this paper, I will give a summary of the recently completed work during which we developed and validated a radiative transfer model of a pyrotechnic flare. The model allows us to make predictions of the flux emitted from the flame. Further details concerning this research can be found in the final report.[1]

In this paper, I will first present the model and its theoretical basis, next experimental data needed for the model validation, and finally a comparison of experiment with the model.

THEORETICAL

It was hypothesized that the flux radiated from a flame of burning magnesium, sodium nitrate, and binder consists mainly of photons from the resonance transition of the sodium D lines. If this were the case, we should be able to predict radiative output by treating only the sodium D radiation. It is on this basis that the radiative model was developed.

We know that the total radiant intensity $I_{\nu\mu}(\tau)$ at frequency ν in a direction described by $\mu = \cos\Theta$ and issuing from a volume element at optical depth τ is given by the radiative-transfer equation[2]

$$dI_{\nu\mu}(\tau)/d\tau = \phi_{\nu a}[I_{\nu\mu}(\tau) - S_{\nu}(\tau)] \ . \qquad (1)$$

The optical depth τ is related to the physical depth z by $\tau_{\nu} = \int k_{\nu} dz$, where k_{ν} is the linear absorption coefficient of the flame. The normalized spectral two-line profile of the absorption coefficient $\phi_{\nu a}$ is a function which takes account

of flame line broadening mechanisms. The line-source function $S_\nu(\tau)$ accounts for increments or decrements in the radiant intensity from a volume element at optical depth τ due to emitters and absorbers within that volume element. It is defined at a given frequency by $S_\nu \equiv \varepsilon_\nu / k_\nu$, where ε_ν is the monochromatic volume emission coefficient.

Formal integration of the transfer equation yields the expression

$$I_{\nu 1} = I_{\nu 2} \exp[-(\tau_2 - \tau_1)\phi_{\nu a}/\mu] + \int_{\tau=\tau_1}^{\tau=\tau_2} [S_\nu(\tau)\phi_{\nu a}/\mu] \exp[-(\tau - \tau_1)\phi_{\nu a}/\mu] d\tau , \tag{2}$$

where τ_1 and τ_2 are the optical depth integration limits from front to the rear of the atmosphere respectively, and $I_{\nu 1}$ and $I_{\nu 2}$ are the spectral intensity at optical depths τ_1 and τ_2 respectively. In order to solve the transfer equation, for the observed radiant intensity, the flame is represented by the following model.

(1) The flame is a homogeneous gaseous atmosphere with plane-parallel stratification.

(2) The gas consists of inert molecules plus sodium atoms which can be excited to the $^2P_{\frac{1}{2}}$ or $^2P_{\frac{3}{2}}$ level.

(3) There is local thermodynamic equilibrium LTE governed by the local temperature.

(4) Energy exchange by radiation leads to radiative equilibrium.

(5) The refractive index of the medium is unity.

(6) The radiation is unpolarized when emitted and remains unpolarized in its interactions with flame species.

(7) The temperature gradient can be represented by a parabola whose vertex is at the center of the flame.

(8) The absorption profile $\phi_{\nu a}$ and number density of sodium atoms N_0 have average values, inside the flame, that are independent of τ.

The form of Eq. (2) has been simplified for the present case, namely (a) the observed flux is that emerging normal to the surface (μ=1), (b) no flux is incident on the rear surface of the atmosphere ($I_{\nu\ell}$=0), and (c) $S_\nu(\tau) = B_\nu(T')$ for the LTE case where $B_\nu(T')$ is the Planck function. Under these conditions, integrating from the front surface, where z and τ_1 are 0, to the rear surface where $\tau_\ell = T$, the total optical thickness, the monochromatic emergent intensity is

$$I_\nu^\circ = \phi_{\nu a}\int_{\tau=0}^{\tau=T} B_\nu(T')\exp(-\tau\phi_{\nu a})d\tau \ . \qquad (3)$$

The theoretical relative spectral radiant power $\phi_{\nu a}$, proportional to spectral emergent intensity I_ν° for a particular model, was found by numerical integration of Eq. (3) using Simpson's rule of 2m intervals. Each computed spectrum Φ_λ, normalized to a power maximum of unity, is plotted for comparison with the corresponding experimental flare spectrum Φ_λ' in Figs. 1 and 2.

Parameters of the theory that must be supplied from properties of the flame are (1) optical thickness $\tau(z)$ as a function of position in the flame, (2) a flame temperature gradient $T'(z)$ as a function of position in the flame, and (3) the scattering profile a parameter in $\phi_{\nu a}$.

EXPERIMENTAL

The test flares were composed of 50 g of a magnesium-sodium nitrate-binder mixture compressed into 3.3 cm i.d. by 5.5 cm long paper tubes, having formulas shown in Table 1. Formula groups 1, 2, and 3 are nearly stoichiometric mixtures, the sodium nitrate in groups 2 and 3 being .1 and .01 of group 1 respectively. Stoichiometry was maintained in groups 2 and 3 by addition of potassium nitrate chosen because it reacts with magnesium at about the same rate as sodium nitrate and because of its low-emissivity in the neighborhood of the sodium D lines, the region of interest for these studies.

Each of three differen illuminating composition formulas was tested in air at 8 levels of pressure; namely 760, 630, 300, 225, 150, 75, 30 and 6 torr. For each pressure-formula combination, the burning time, flame size, and relative spectral radiant power distribution in the visible region were recorded.

Relative radiant power spectra Φ_λ' of typical flares for each pressure-formula combination are plotted in Figs. 1 and 2. The solid curves in Figs. 1 and 2 are the experimental data. These spectra are normalized to a peak value of unity for convenience in the first step of the theoretical comparison. Spectra were not obtained for formula groups 2 and 3 at 6 torr because the flares did not sustain combustion at this pressure. Group 1 flares at 6 torr barely burned. Combustion difficulty was visually observable for all flares tested at 75 torr or less.

Values of the physical flame depth z' range from 6 cm for formula group 1, 760 torr to 2.5 cm for formula group 3, 30 torr, a rather narrow range considering the large range of experimental conditions.

DISCUSSION

Visual comparison of the theoretical Φ_λ and experimental Φ_λ' relative radiant power spectra, plotted in Figs. 1 and 2, shows that the distribution computed from theory agrees quite well with the experimental distribution for each pressure-formula combination.

In summary, it has been shown that the spectral radiant power distribution of a pyrotechnic illuminating flare flame can be predicted by a two-line radiative transfer model which has been described. This can be done without introducing assumptions which require *ad hoc* modifications of the model to describe different flares. Known system variables such as flare formula, flare size, and ambient pressure are the necessary and sufficient input needed for the theoretical prediction.

REFERENCES

1. B. E. Douda, *Radiative Transfer Model of a Pyrotechnic Flame*, RDTR No. 258, Naval Ammunition Depot, Crane, Indiana (1973). Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22151. AD# 769237.

2. D. G. Hummer, J. Quant. Spectrosc. Radiat. Transfer 8, 193 (1968).

TABLE 1. Flare Formulations

Ingredients	Formula Groups 1	2	3
Magnesium	44.0[a]	40.4	40.04
Sodium nitrate	51.5	5.15	0.515
Potassium nitrate	--	49.95	54.945
Epoxy binder mix	4.5	4.5	4.5

[a]Percent by weight

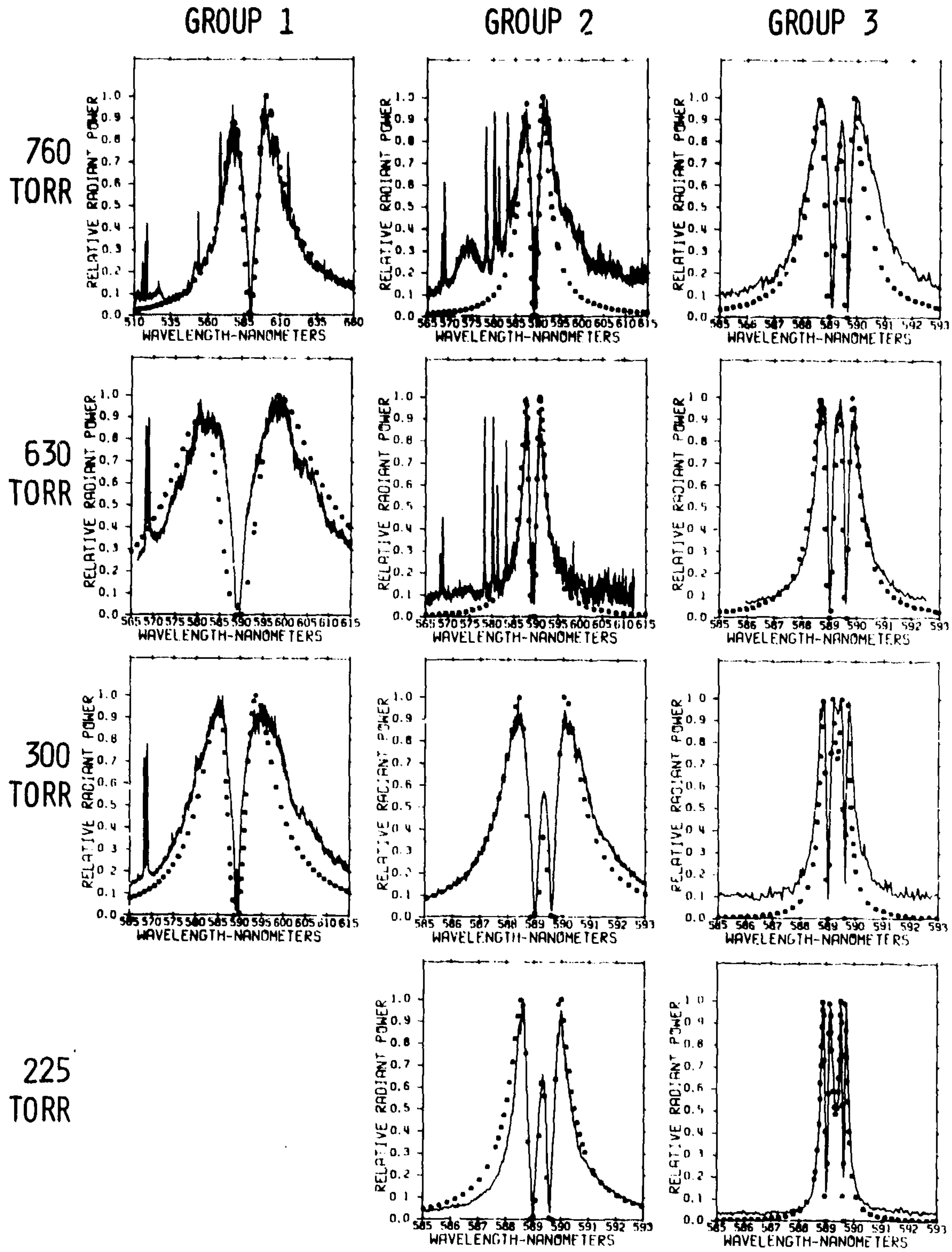

Fig. 1. Illuminating Flare Flame Spectra for formula groups 1, 2, and 3 at 4 levels of ambient pressure. Theoretical relative radiant power values Φ_λ are indicated by boxes (■). Experimentally determined relative radiant power values Φ_λ' are shown by the solid line.

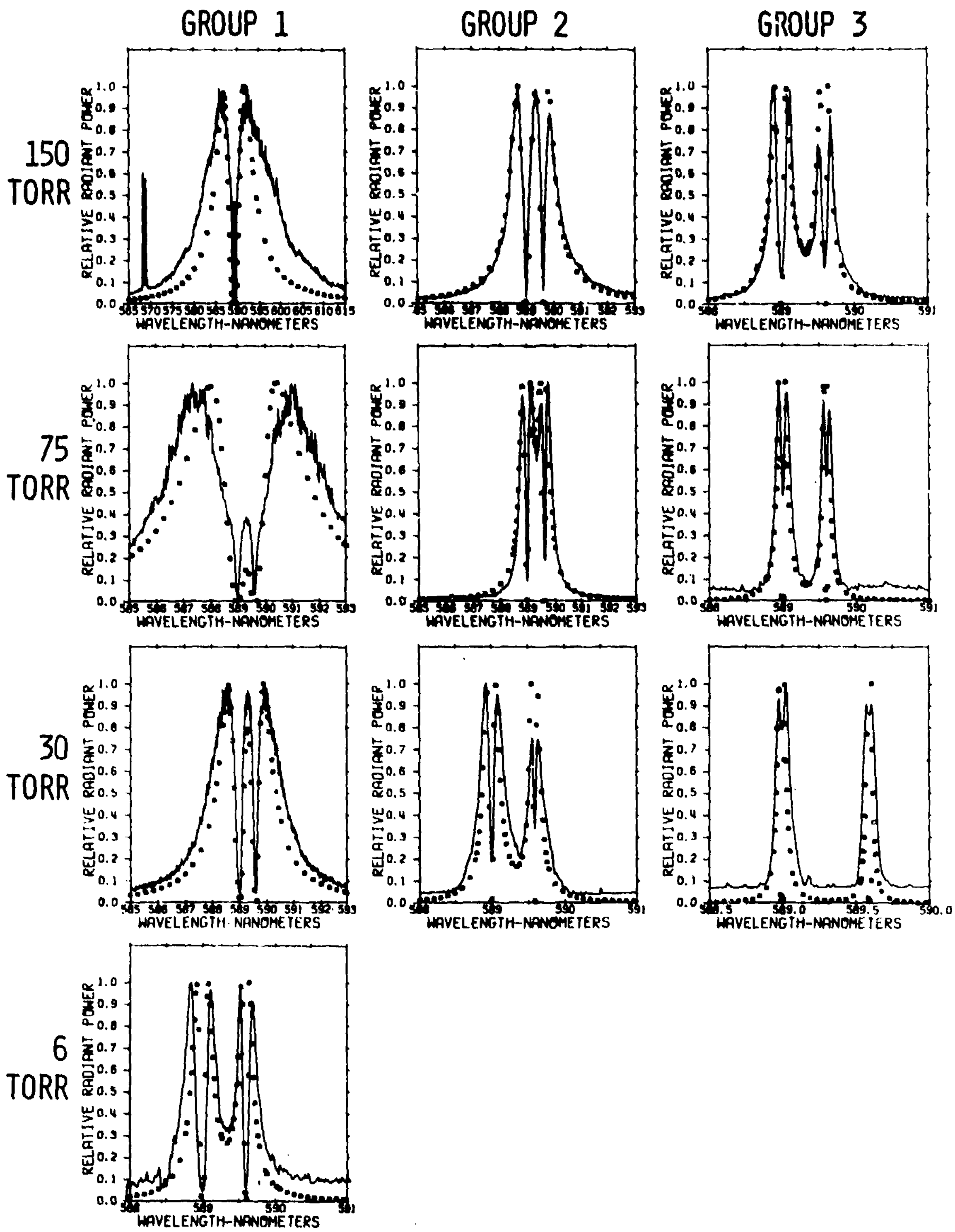

Fig. 2. Illuminating Flare Flame Spectra for formula groups 1, 2, and 3 at 4 levels of ambient pressure. Theoretical relative radiant power values Φ_λ are indicated by boxes (■). Experimentally determined relative radiant power values Φ_λ' are shown by the solid line.